Nonlinear Silicon Photonics

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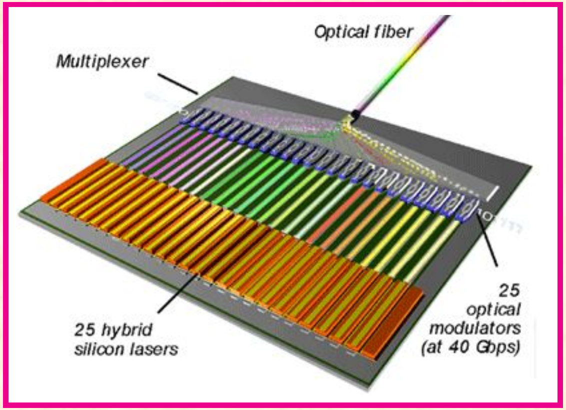
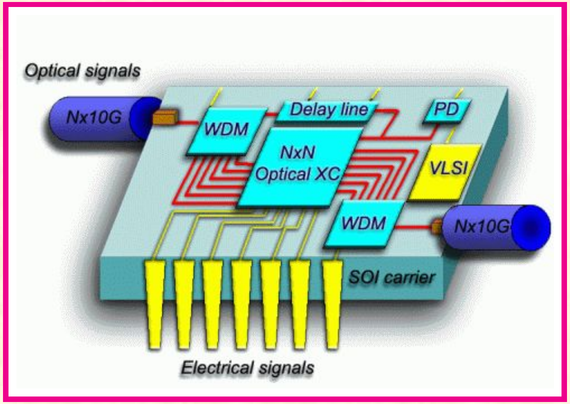
Outline

- Introduction to Silicon Photonics
- Self-Phase Modulation and Soliton Formation
- Higher-Order Solitons and Supercontinuum Generation
- Cross-Phase Modulation and Optical Switching
- Nonlinear Polarization Rotation and Ultrafast Switching
- Raman Amplification and Silicon Raman Lasers
- Four-Wave Mixing and its Applications
- Concluding Remarks

Silicon Photonics

- Silicon dominates microelectronics industry totally.
- Silicon photonics is a new research area trying to capitalize on the huge investment by the microelectronics industry.
- It has the potential for providing a monolithically integrated optoelectronic platform on a silicon chip.





Credit: Intel and IBM Websites

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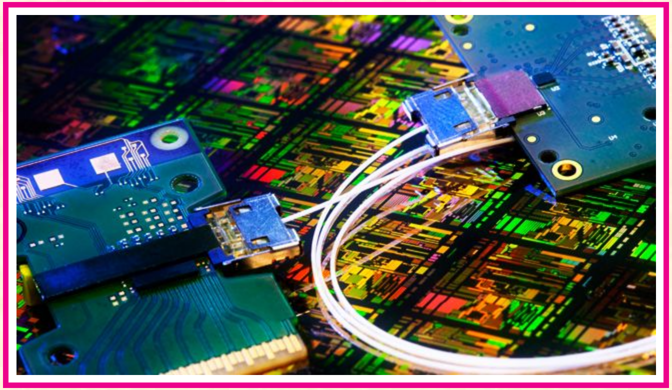
Silicon Photonics

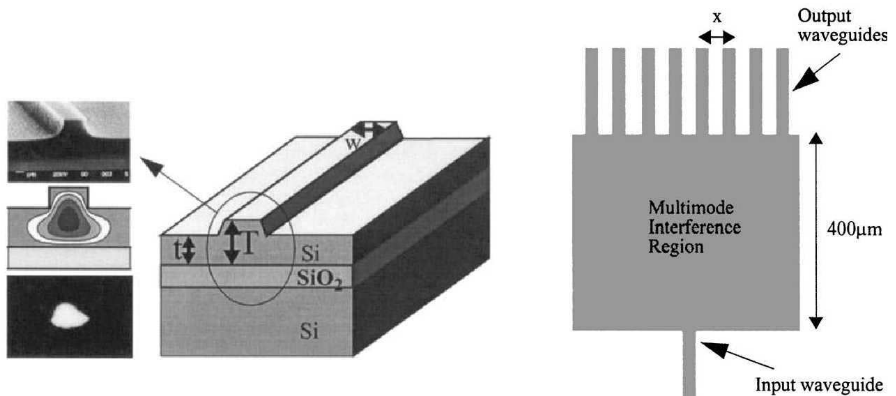


- Intel introduced 50-Gb/s silicon-photonics links in 2010.
- Transmitter chip contains four hybrid silicon lasers and four optical modulators, each encoding data at 12.5 Gb/s.
- Four data streams are combined and fed into a single optical fiber.
- Receiver chip separates four WDM channels and directs them into separate photodetectors.

Siliocn Nanowires

- Optical processing on a silicon chip requires photonic wires.
- They confine light just as electric wires confine electrons.
- Best solution: A silicon-on-insulator (SOI) waveguide in which a narrow silicon layer is surrounded by lower-index cladding layers.
- In a SOI waveguide, the thin silicon layer has a silica-glass layer at bottom and air or a polymer on top.
- Since a silicon substrate is used, it is not obvious how to crate a silica layer just below the silicon surface.
- Silicon-on-Insulator Technology was developed to meet this need and its development has led to the new research area of **silicon photonics**.

Silicon-on-Insulator Technology



(a)

(b)

- Silica layer formed by implanting oxygen, followed with annealing.
- A rib or ridge structure used to confine light tightly within an effective mode area of $< 0.5\ \mu$m^2.
- Nonlinear effects enhanced considerably at moderate power levels.
- Future circuits will need nonlinear effects for signal processing.

Nonlinear Effects and their Applications

- Self-Phase Modulation (SPM)
  Soliton-like pulse evolution, supercontinuum generation, all-optical regeneration of telecom channels
- Cross-Phase Modulation (XPM)
  Photonic switching, wavelength conversion, optical signal processing, polarization changes through TE–TM mode coupling
- Four-Wave Mixing (FWM)
  Parametric amplification, wavelength conversion, phase conjugation, tunable parametric delays
- Stimulated Raman Scattering (SRS)
  Raman amplification at any wavelength, optically pumped Raman lasers

Kerr Effect and Two-Photon Absorption

- Refractive index depends on local intensity (Kerr effect):

$$n(\omega, I) = \bar{n}(\omega) + n_2(1 + ir)I(t).$$

- Material parameter $n_2 = 3 \times 10^{-18}$ m^2/W is larger for silicon by a factor of 100 compared with silica fibers.
- Dimensionless parameter $r = \beta_{\mathrm{TPA}}/(2k_0 n_2)$ is related to two-photon absorption (TPA) occurring when $h\nu$ exceeds $E_g/2$.
- TPA parameter: $\beta_{\mathrm{TPA}} = 5 \times 10^{-12}$ m/W at wavelengths near 1550 nm.
- Dimensionless parameter $r \approx 0.1$ for silicon near 1550 nm.
- TPA is a major limiting factor for SOI waveguides because it creates free carriers (in addition to nonlinear losses).

Free-Carrier Generation

- TPA creates free carriers inside a silicon waveguide according to

$$\frac{\partial N_c}{\partial t} = \frac{\beta_{\mathrm{TPA}}}{2h\nu_0} I^2(z,t) - \frac{N_c}{\tau_c}.$$

- Carrier lifetime is relatively large for silicon ($\tau_c > 10$ ns).

- It limits the device response time if carriers cannot be removed quickly enough.

- Free carriers also introduce loss and change the refractive index.

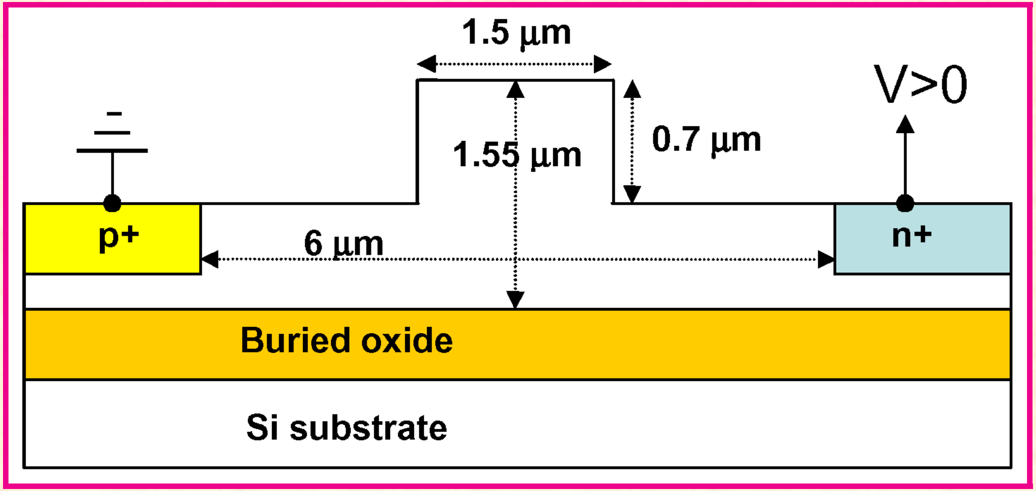
- Pulse propagation inside silicon waveguides is governed by

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = ik_0 n_2(1+ir)|A|^2 A - \frac{\sigma}{2}(1+i\mu)N_c A - \frac{\alpha_l}{2}A.$$

Free-Carrier Absorption (FCA)

- Loss induced by FCA: $\alpha_f = \sigma N_c$ with $\sigma = 1.45 \times 10^{-21}$ m^2.
- Free carriers also change the refractive index by $\Delta n = -(\mu/2k_0)\sigma N_c$ (free-carrier dispersion).
- This change is opposite to the index change $n_2 I$ resulting from the Kerr effect.
- Parameter μ is known as the "linewidth enhancement factor" in the context of semiconductor lasers.
- Its value for silicon is close to 7.5 in the spectral region near 1550 nm.
- Absorption and index changes resulting from free carriers affect the performance of silicon waveguides.
- Quick removal of carriers helps (e.g., by applying a dc electric field).

Removal of Free Carriers



Jones et al, Opt. Exp. **13**, 519 (2005)

- A reversed-biased p-n junction is used for this purpose.
- Electric field across the waveguide removes electrons and holes.
- Drift time becomes shorter for larger applied voltages.
- Effective carrier lifetime can be shortened from >20 to <1 ns.

Self-Phase Modulation (SPM)

- Refractive index depends on intensity as $n' = \bar{n} + n_2 I(t)$.
- Propagation constant also becomes intensity-dependent:

$$\beta' = \beta + k_0 n_2 (P/A_{\rm eff}) \equiv \beta + \gamma P.$$

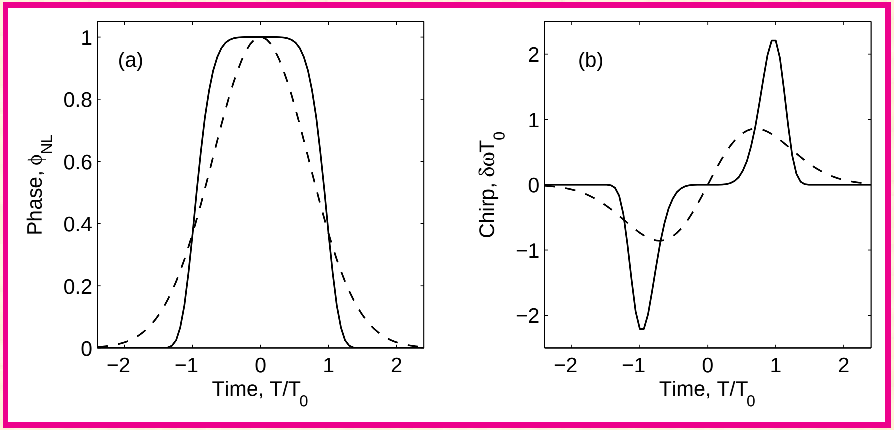
- $\gamma = k_0 n_2 / A_{\rm eff}$ is larger for silicon nanowires by a factor of >10,000 compared with silica fibers.
- Nonlinear Phase shift:

$$\phi_{\rm NL} = \int_0^L (\beta' - \beta)\, dz = \int_0^L \gamma P(z)\, dz = \gamma P_{\rm in} L_{\rm eff}.$$

Here, $P(z) = P_{\rm in} e^{-\alpha z}$ and $L_{\rm eff} = (1 - e^{-\alpha L})/\alpha$.

- Optical field modifies its own phase (SPM).
- Phase shift varies with time for pulses (chirping).

Chirping and Spectral Broadening



- In the case of optical pulses, $\phi_{\text{NL}}(t) = \gamma P(t) L_{\text{eff}}$.
- Chirp is related to the phase derivative $d\phi_{\text{NL}}/dt$.
- Phase and chirp profiles for super-Gaussian pulses are shown using $P(t) = P_0 \exp[-(t/T)^{2m}]$ with $m = 1$ and $m = 3$.
- SPM creates new frequencies and leads to spectral broadening.

Self-Phase Modulation and TPA

- Preceding analysis neglected two-photon absorption.
- Its impact on SPM can be studied by solving:

$$\frac{\partial A}{\partial z} = i\gamma(1+ir)|A|^2 A - \frac{\alpha_l}{2}A.$$

- This equation ignores dispersive and free-carrier effects.
- Using $A = \sqrt{P}\exp(i\phi_{\rm NL})$, we obtain the following analytic solution:

$$P(L,t) = \frac{P(0,t)\exp(-\alpha_l L)}{1+2r\gamma P(0,t)L_{\rm eff}},$$

$$\phi_{\rm NL}(L,t) = \frac{1}{2r}\ln[1+2r\gamma P(0,t)L_{\rm eff}].$$

- TPA converts linear dependence of $\phi_{\rm NL}$ on power to a logarithmic one.

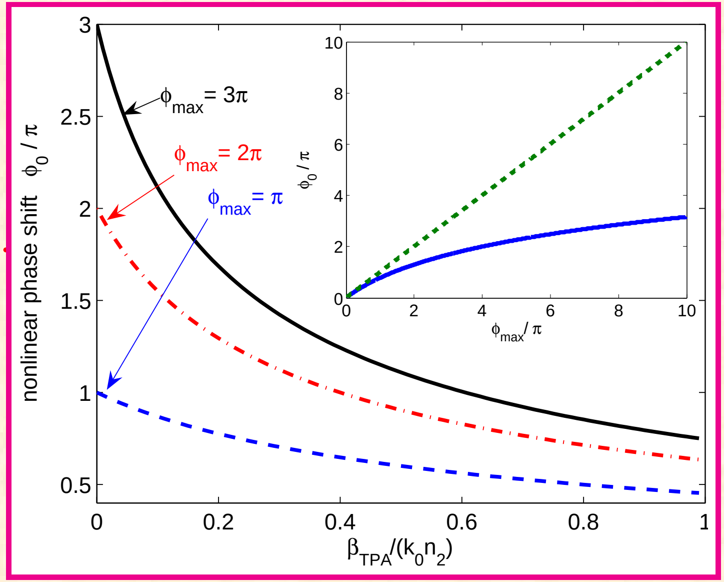
Impact of Two-Photon Absorption

- TPA reduces the maximum phase shift:

  $$\phi_0 = \ln(1 + 2r\phi_{\max})/(2r).$$

- In the absence of TPA, $\phi_0 = \phi_{\max} = \gamma P_0 L_{\text{eff}}$.

- Inset shows the reduction using $r = 0.1$.



Yin, Agrawal, Opt. Lett. **32**, 2031 (2007)

- TPA-induced reduction becomes severe at high powers.
- When $\phi_{\max} = 100$, ϕ_0 is limited to a value of 15.

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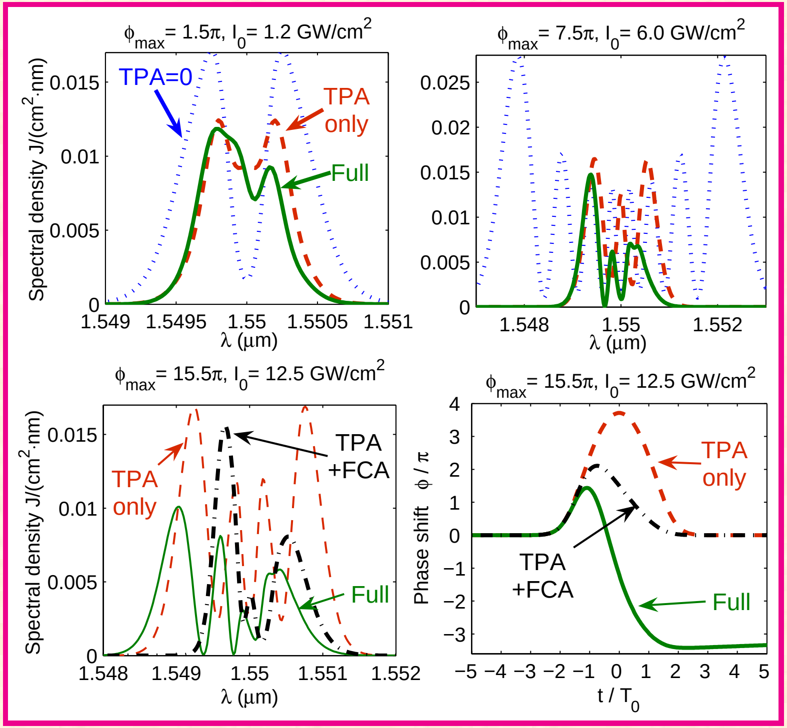
Impact of Free-Carrier Generation

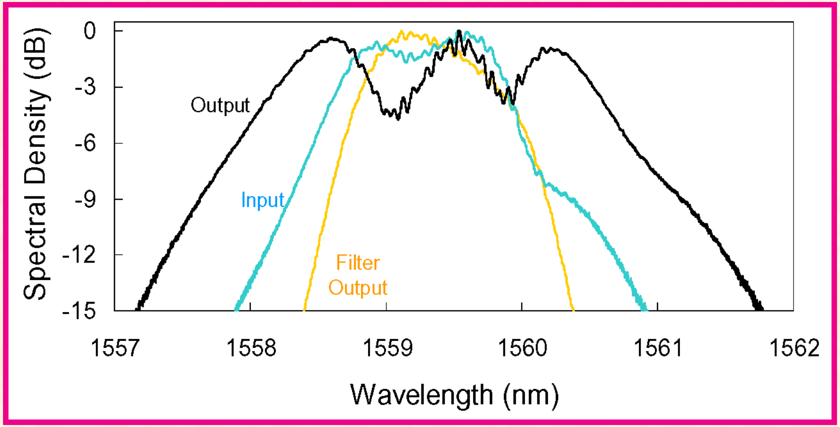


$$P(t) = P_0 e^{-t^2/T^2}$$
$$T_0 = 10 \text{ ps}$$
$$L = 2 \text{ cm}$$
$$\tau_c = 1 \text{ ns}$$
$$\alpha_l = 1 \text{ dB/cm}$$

Yin and Agrawal, Opt. Lett. **32**, 2031 (2007)

Free carriers produce a nonlinear phase shift in the opposite direction.

Experimental Results



Boyraz et al., Opt. Exp. **12**, 829 (2004).

- First observation of SPM-induced spectral broadening in 2004.
- 4-ps pulses launched inside a 2-cm-long SOI waveguide.
- The 3-peak output spectrum broadened by a factor of 2 when peak intensity was 2.2 GW/cm^2 ($P_0 \approx 100$ W).

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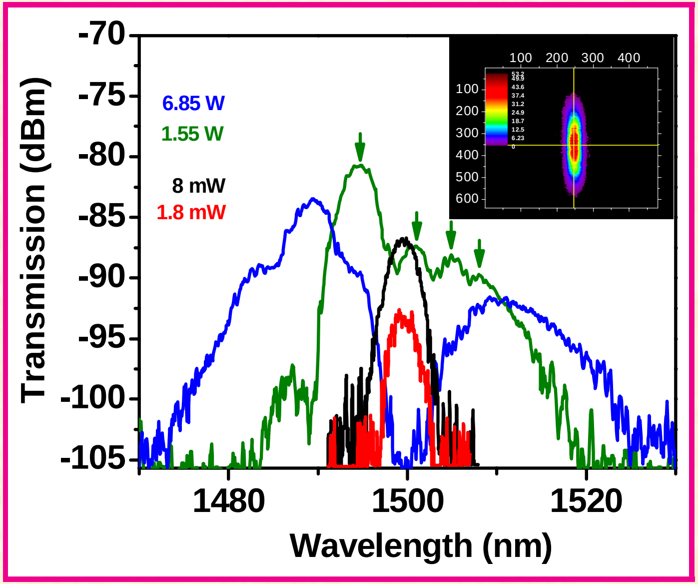
Experimental Results



Dulkeith et al., Opt. Exp. **14**, 5524 (2006).

- Larger broadening by 2006.
- 1.8-ps pulses launched inside a 4-mm-long waveguide.
- Width 470 nm height 226 nm.
- Spectral asymmetry is due to free-carrier effects.
- Inset shows the FROG trace.

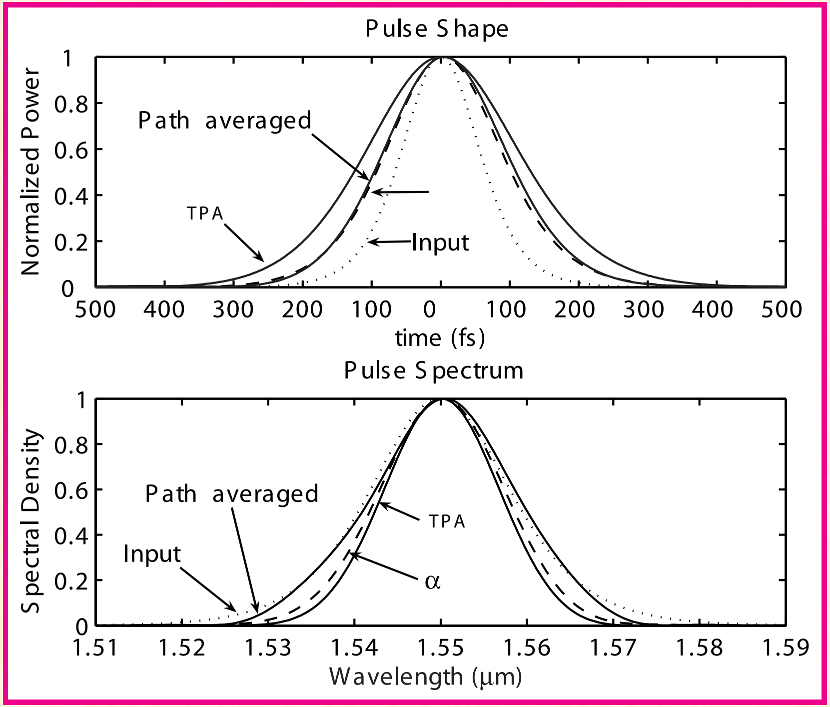
Formation of Optical Solitons

- Solitons balance SPM with dispersion and maintain their shape.
- Nonlinear length $L_{\mathrm{NL}} = 1/(\gamma P_0)$ ~1 mm at peak powers <100 W.
- Dispersion length, $L_D = T_0^2/|\beta_2$, can be ~1 mm for fsec pulses.
- Pulses propagate as fundamental solitons when $\beta_2 < 0$ and

$$N^2 = \frac{L_D}{L_{\mathrm{NL}}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} = 1.$$

- Perfect solitons do not exist because of TPA and other losses.
- Soliton-like propagation still possible with proper design.
- Numerical simulations and experiments confirm this expectation. Zhang et al. Opt. Express **15**, 7682 (2007).

Numerical Results



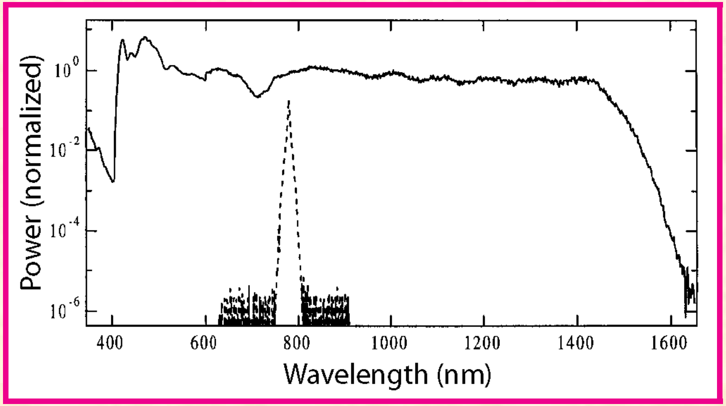
Yin, Lin, and Agrawal, Opt. Lett. 31, 1295 (2006)

130-fs pulses launched inside a 5-mm-long waveguide ($N = 1$).

Supercontinuum Generation

- Ultrashort pulses are affected by a multitude of nonlinear effects, such as SPM, XPM, FWM, and SRS, together with dispersion.
- All of these nonlinear processes are capable of generating new frequencies outside the input pulse spectrum.
- For sufficiently intense pulses, the pulse spectrum can become so broad that it extends over a frequency range exceeding 100 THz.
- Such extreme spectral broadening is referred to as *supercontinuum generation*.
- This phenomenon was first observed in solids and gases more than 35 years ago (late 1960s.)
- Since 2000, microstructure fibers have been used for supercontinuum generation.

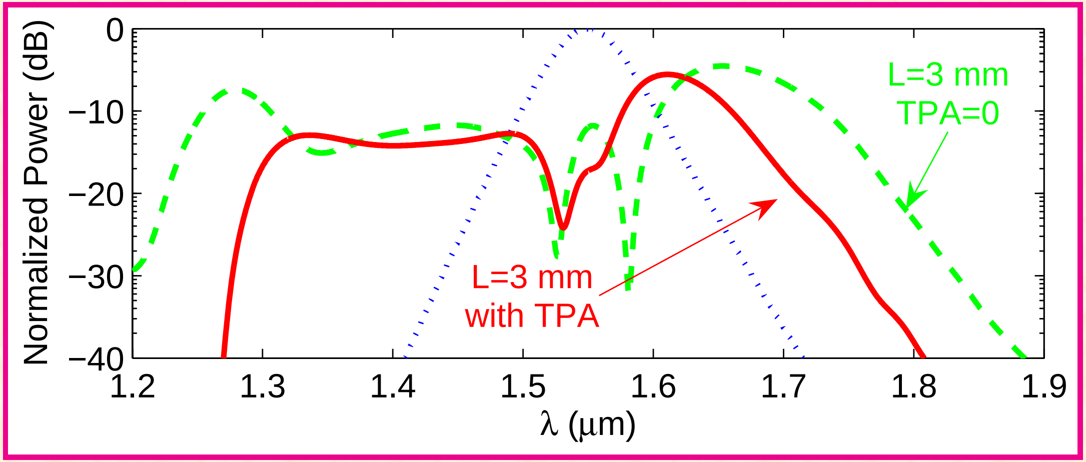
SC Generation in a microstructured fiber



Ranka et al., Opt. Lett. **25**, 25 (2000)

- Output spectrum generated in a 75-cm section of microstructured fiber using 100-fs pules with 0.8 pJ energy.
- Even for such a short fiber, supercontinuum extends from 400 to 1600 nm.
- Supercontinuum is also relatively flat over the entire bandwidth.

SC Generation in Silicon Waveguides



Yin, Lin, and Agrawal, Opt. Lett. **32**, 391 (2007)

- TPA reduces SC bandwidth but is not detrimental.
- Nearly 400-nm-wide supercontinuum created within a 3-mm-long waveguide.
- Required pulse energies are relatively modest ($\sim$1 pJ).

SC Generation in Silicon Waveguides

- SOI waveguides also support higher-order solitons when $N=(\gamma P_0 T_0^2/|\beta_2|)^{1/2}$ exceeds 1.
- Higher-order dispersion should leads to their fission into much shorter fundamental solitons: $T_k = T_0/(2N+1-2k)$.
- Intrapulse Raman scattering absent because of a narrow Raman bandwidth: no significant red-shifting of solitons.
- Similar to the case of optical fibers, each soliton emits dispersive waves on the blue side when $\beta_3 > 0$.
- Numerical simulations confirm the potential of SOI waveguides for SC generation.
- Spectral broadening over 350 nm is predicted for femtosecond pulses.

Cross-Phase Modulation

- Consider two optical fields propagating simultaneously.
- Nonlinear refractive index seen by one wave depends on the intensity of the other wave as

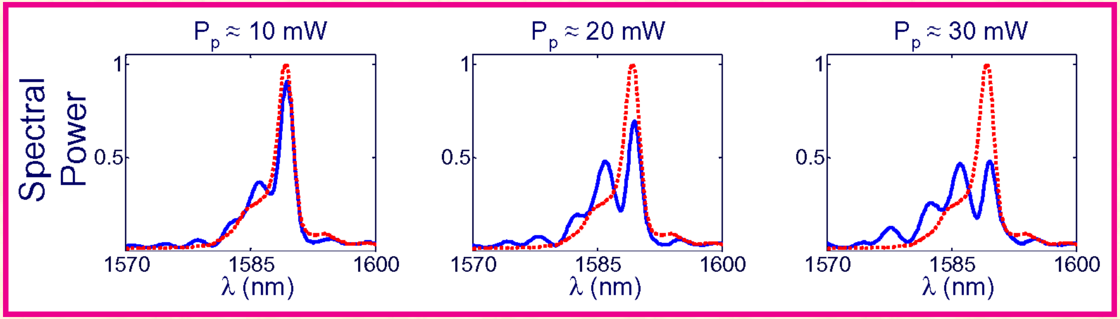
$$\Delta n_{\rm NL} = n_2(|A_1|^2 + b|A_2|^2).$$

- Total nonlinear phase shift in a fiber of length L:

$$\phi_{\rm NL} = (2\pi L/\lambda)n_2[I_1(t) + bI_2(t)].$$

- An optical beam modifies not only its own phase but also of other copropagating beams (XPM).
- XPM induces nonlinear coupling among overlapping optical pulses.

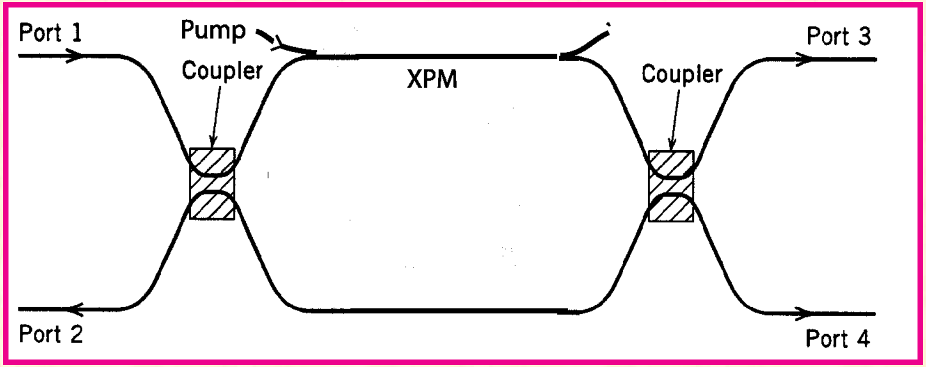
XPM-Induced Spectral Changes



Hsieh et al., Opt. Exp. **15**, 1135 (2007)

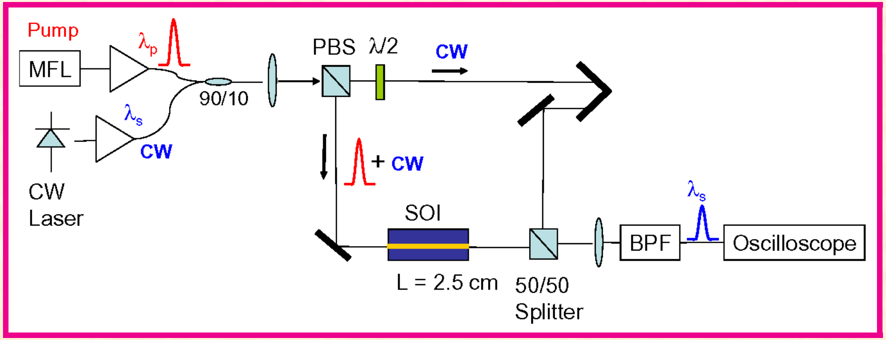
- 200-fs pump and probe pulses (at 1527 and 1590 nm) launched into a 4.7-mm-long SOI waveguide ($w = 445$ nm, $h = 220$ nm).
- Pump and probe pulses travel at different speeds (walk-off effect).
- XPM-induced phase shifts occurs as long as pulses overlap.
- Asymmetric XPM-induced spectral broadening depends on pump power (blue curve); Probe spectra without pump (red curve).

XPM-Induced Switching



- A Mach–Zehnder interferometer is often used for optical switching.
- Output switched to a different port using a control signal that shifts the phase through XPM.
- If control signal is in the form of a pulse train, a CW signal can be converted into a pulse train.
- Turn-on time quite fast but the generation of free carriers widens the switching window (depends on the carrier lifetime).

Experimental Demonstration



Boyraz et al., Opt. Exp. **12**, 4094 (2004)

- A Mach–Zehnder interferometer used for optical switching.
- Short pump pulses (<1 ps) at 1560 nm pass through the arm containing a 2.5-cm-long SOI waveguide.
- CW probe experiences XPM-induced phase shift in that arm.
- Temporal slice of the probe overlapping with the pump is optically switched.

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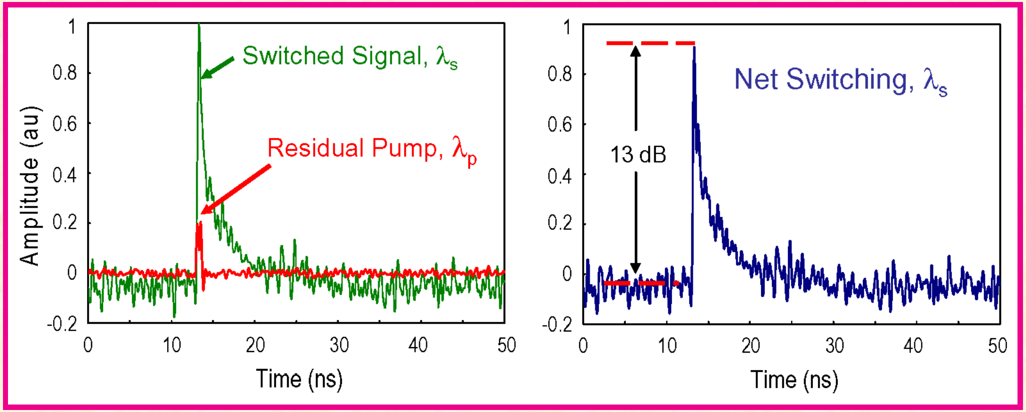
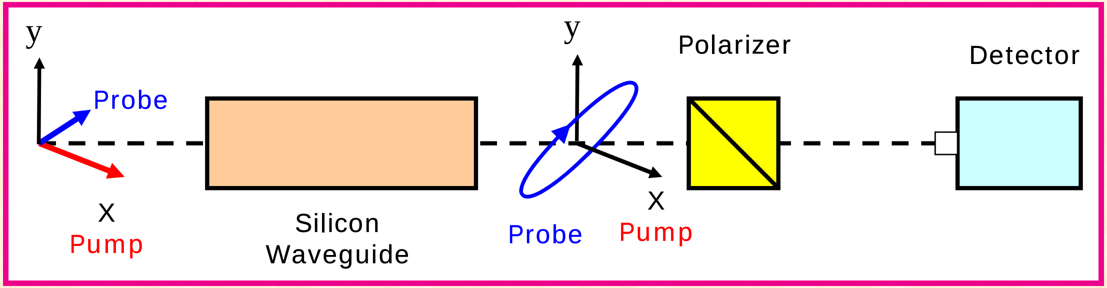
XPM-Induced Switching



Boyraz al., Opt. Exp. **12**, 4094 (2004)

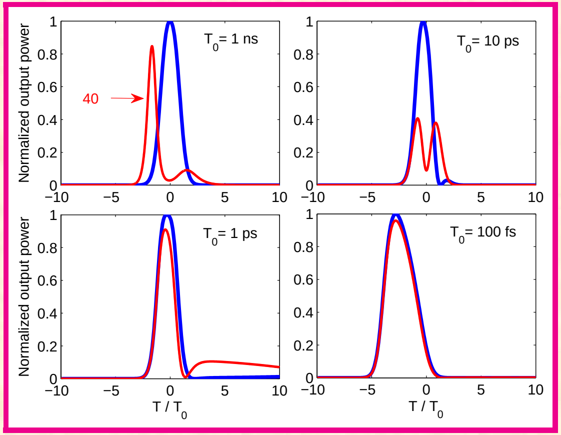
- Instantaneous switching on the leading edge, as expected, with high on–off contrast.
- Long trailing edge results from the free-carrier effects.
- Free carriers provide an additional contribution to the probe phase by changing the refractive index.

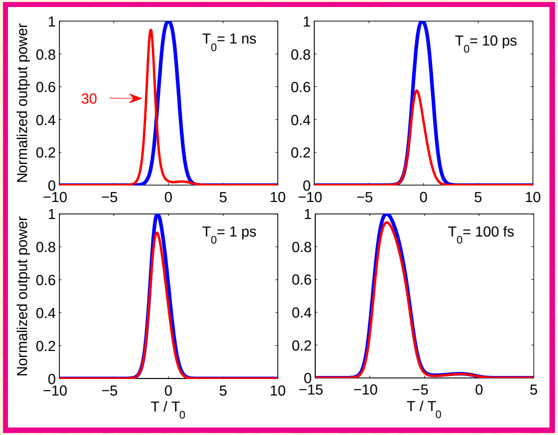
Polarization-Based Kerr Switching



- Pump pulse propagates in the TE mode of a silicon waveguide.
- CW probe polarized at 45° excites TE and TM modes.
- Its TE component acquires an XPM-induced phase shift.
- Output probe elliptically polarized (nonlinear polarization rotation).
- Probe transmitted through the analyzer only when a pump pulse opens the Kerr gate.

Numerical Results

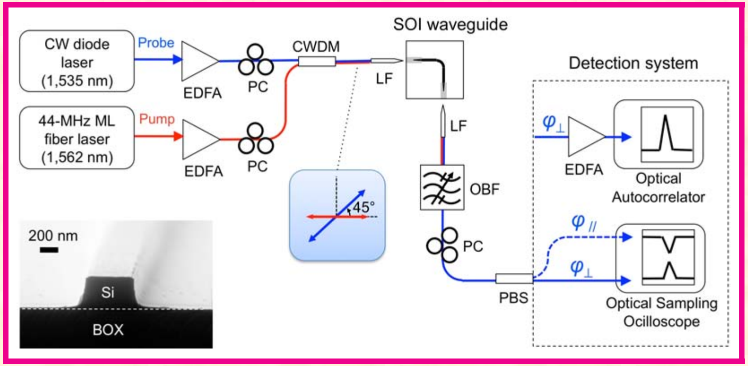




Yin et al., Opt. Lett. **34**, 476 (2009)

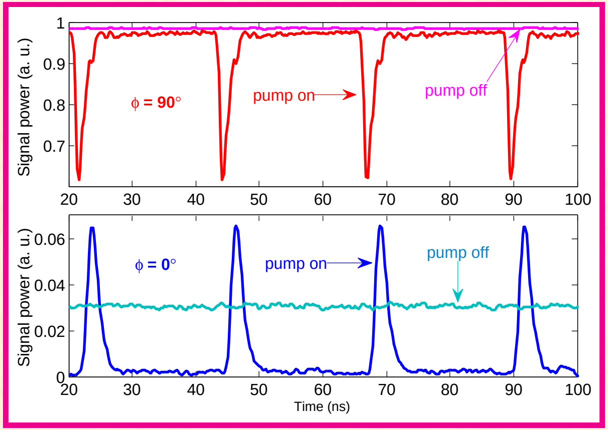
- Switching windows (red) for 4 different pump pulses (blue).
- Cross section: (left) 650×450 nm^2 and (right) 450×450 nm^2.
- Free-carrier and walk-off effects play important roles.
- Free-carrier effects reduced for short pump pulses.
- Birefringence effects minimized for square waveguides.

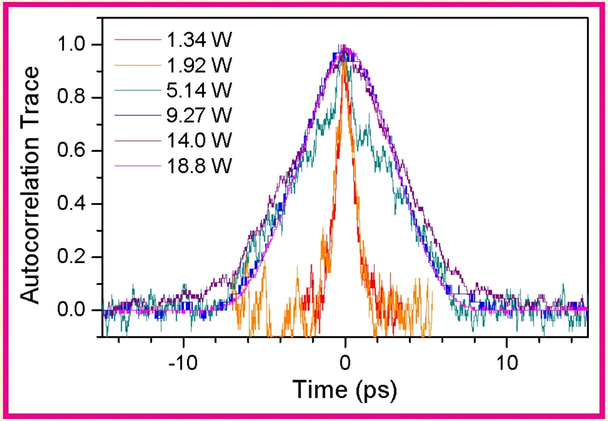
Experimental Setup



- Two EDFAs and PCs used for pump and probe (CW) signals.
- CWDM coupler combines the pump and probe.
- Optical bandpass filter (OBF) blocks the pump.
- Linear birefringence canceled by the PC at the output end.
- PBS helps us to display both probe components simultaneously.

Experimental Results



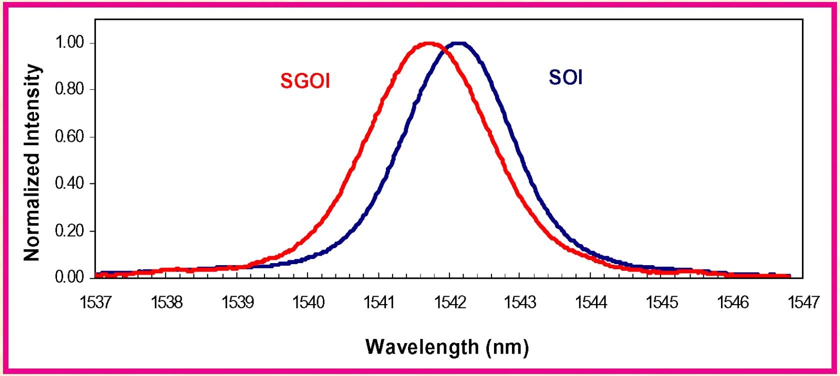


Lee, Yin, Agrawal, Fauchet, Opt. Express **18**, 11514 (2010)

- Blue peaks show normal switching at 44-MHz repetition rate of 500-fs pump pulses.
- Red dips show the case in which each pump pulse blocks the probe transmission.
- Switching window < 1 ps wide at pump powers <2 W.

Stimulated Raman Scattering

- Scattering of a pump beam from vibrating molecules creates a Stokes beam down-shifted in frequency by a specific amount.
- Frequency shift is set by a vibrational mode (phonons).
- Raman gain spectrum exhibits a dominant peak at 15.6 THz with a 105-GHz bandwidth ($\approx$1 nm wide near 1550 nm).
- Peak gain for silicon >1000 larger compared with silica.



Claps et al., Opt. Exp. **13**, 2459 (2006)

Theory behind Raman Amplifiers and Lasers

- Pump and signal powers satisfy a set of two coupled equations:

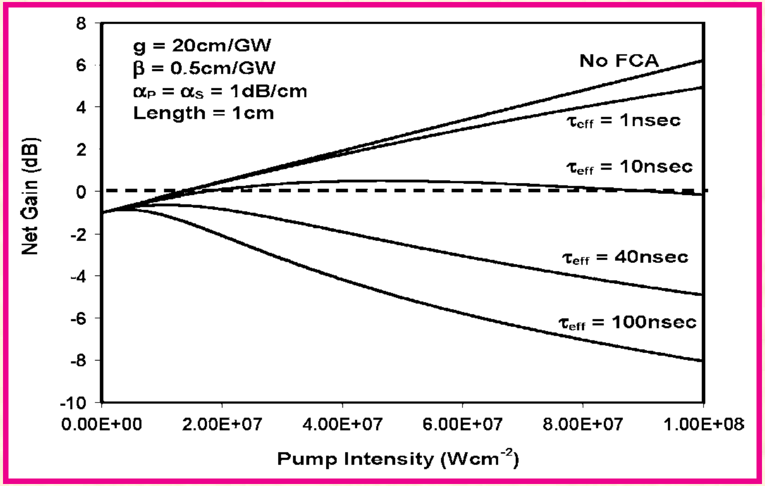
$$\begin{aligned}\frac{\partial P_p}{\partial z} &= -(\alpha_{\rm lp}+\alpha_{\rm fp})P_p - \beta_{\rm pp}P_p^2 - 2\beta_{\rm ps}P_sP_p - g_RP_sP_p\\ \frac{\partial P_s}{\partial z} &= -(\alpha_{\rm ls}+\alpha_{\rm fs})P_s - \beta_{\rm ss}P_s^2 - 2\beta_{\rm sp}P_pP_s + g_RP_pP_s.\end{aligned}$$

- Signal loss by free carriers ($\alpha_{\rm fs} = \sigma_{\rm fc}N$) limits Raman amplification.
- For net amplification to occur, the carrier lifetime should satisfy

$$\tau_0 < \tau_{\rm th} \equiv \frac{\hbar\omega_p(g_R - 2\beta_{\rm sp})^2}{2\alpha_{\rm ls}\sigma_{\rm fc}\beta_{\rm pp}}.$$

- A Raman laser cannot function if this condition does not hold.
  Q. Lin et al., Opt. Express **15**, 16604 (2007).

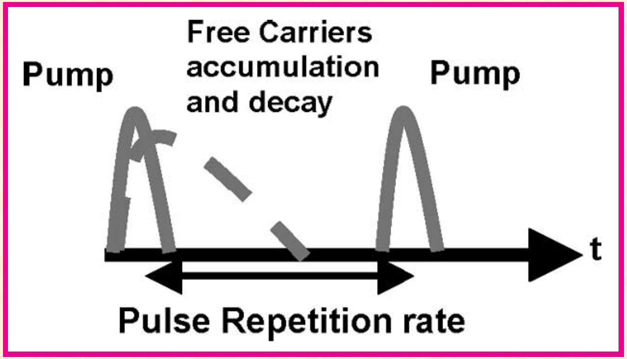
Raman Amplifiers

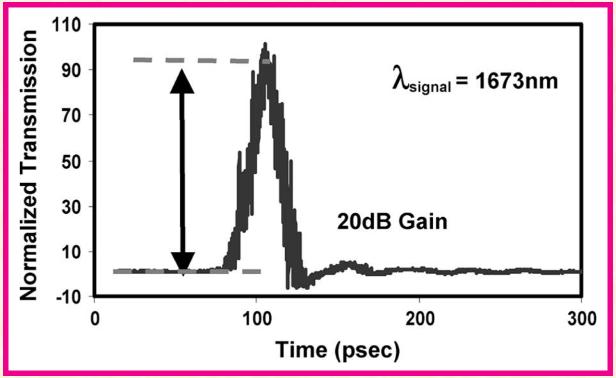


Jalali et al., IEEE JSTQE **12**, 412 (2006)

- CW pumping leads to accumulation of free carriers through TPA.
- Free-carrier absorption introduces losses for pump and signal.
- No signal gain occurs for $\tau_{\text{eff}} > 10$ ns.

Pulsed Raman Amplifiers

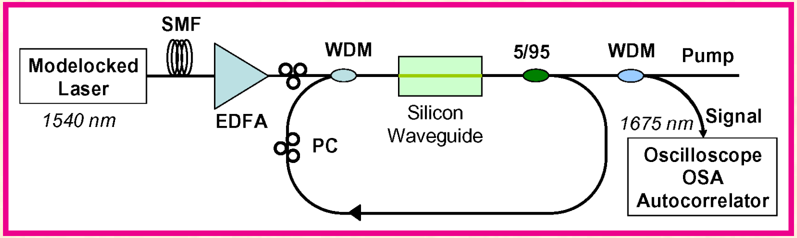


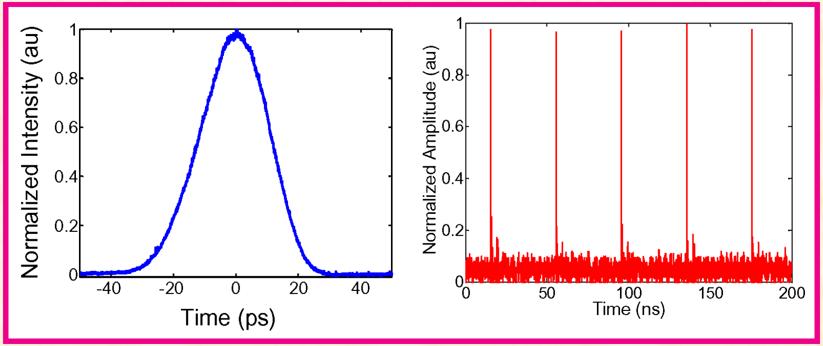


Jalali et al., IEEE JSTQE **12**, 412 (2006)

- Pulsed pumping can provide >20-dB gain if spacing among pulses is much larger than τ_{eff} $(R_p \tau_{\text{eff}} \ll 1)$.
- Free carriers can then decay before the next pulse arrives.
- Pump pulses (∼30 ps) at 1540 used to amplify a 1673-nm signal.
- 20-dB net gain realized at 37-W peak power of pump pulses.

Raman Lasers

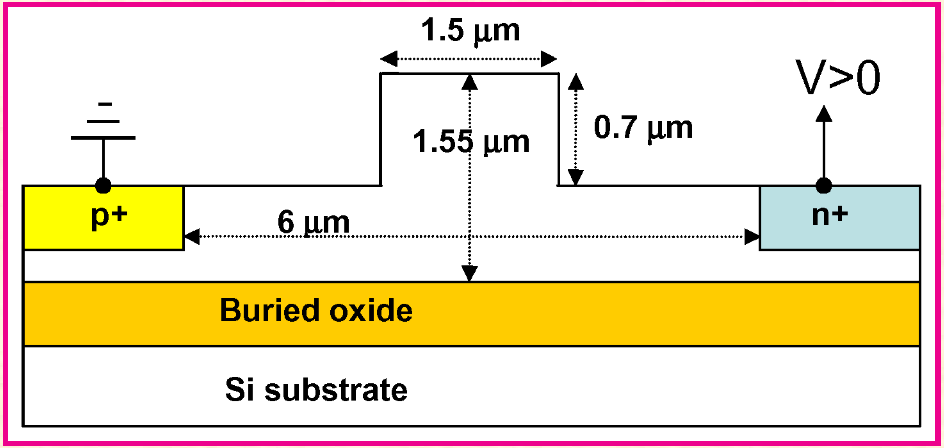




Boyraz and Jalali, Opt. Exp. **12**, 5269 (2004)

- Pumped with 30-ps pulses at 1540 nm at 25-MHz repetition rate.
- Produced 18 ps pulses at 1675 nm at the same repetition rate.

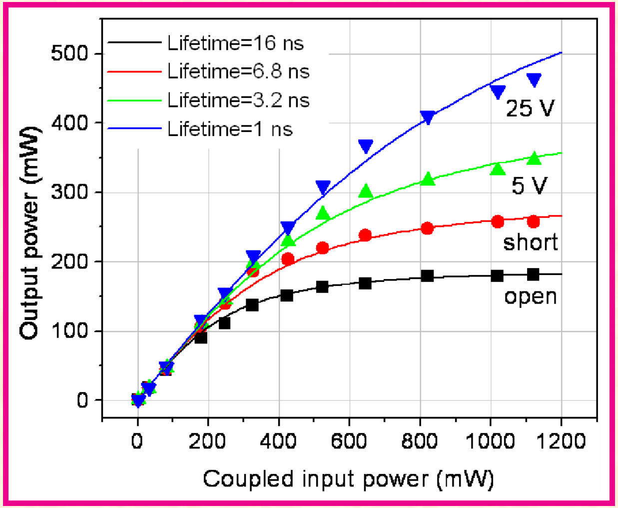
Control of Carrier Lifetime

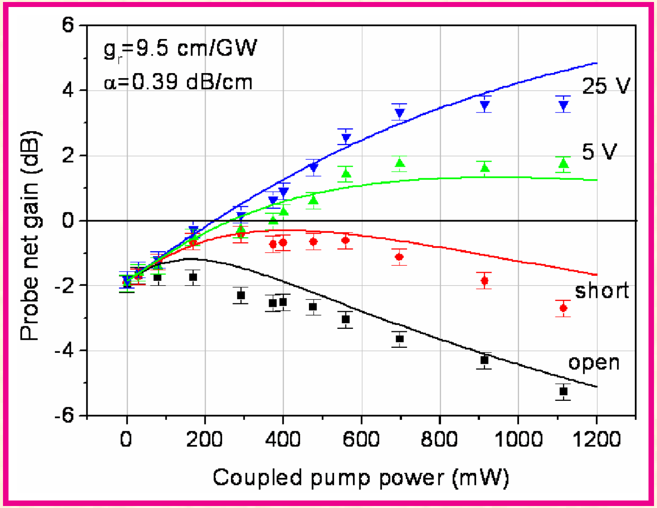


Jones et al, Opt. Exp. **13**, 519 (2005)

- CW pumping can be used if free carriers are removed quickly.
- A reversed-biased p-n junction is used for this purpose.
- Electric field across the waveguide removes electrons and holes.
- Drift time of carriers is shorter for larger applied voltages.

CW Silicon Raman Amplifiers

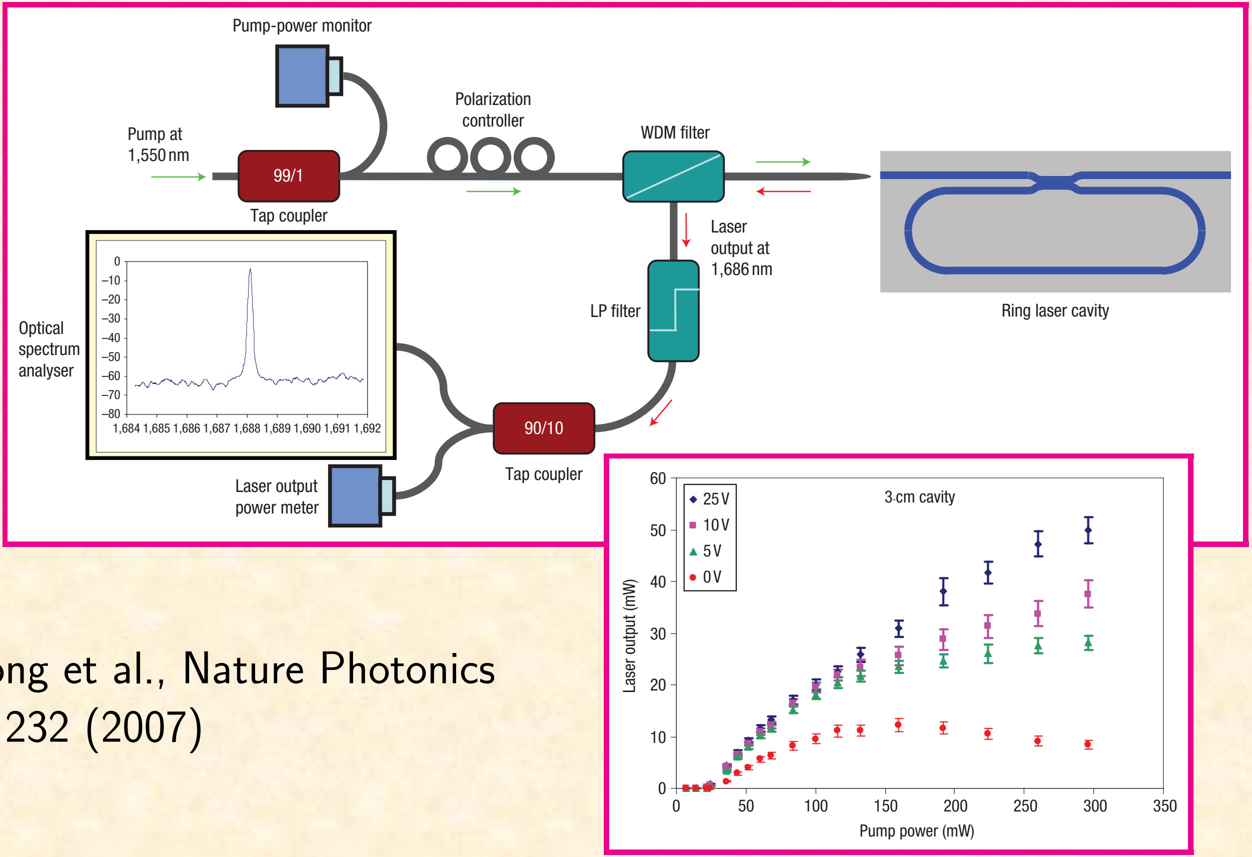




Jones et al, Opt. Exp. **13**, 519 (2005)

- A 4.8-cm-long waveguide CW pumped at 1458 nm (signal at 1684 nm).
- Output pump and signal powers increase with applied voltage.
- Effective carrier lifetime decreases from 16 to 1 ns.

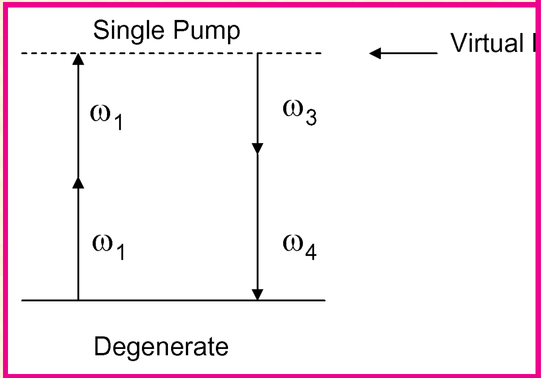
CW Silicon Raman Lasers

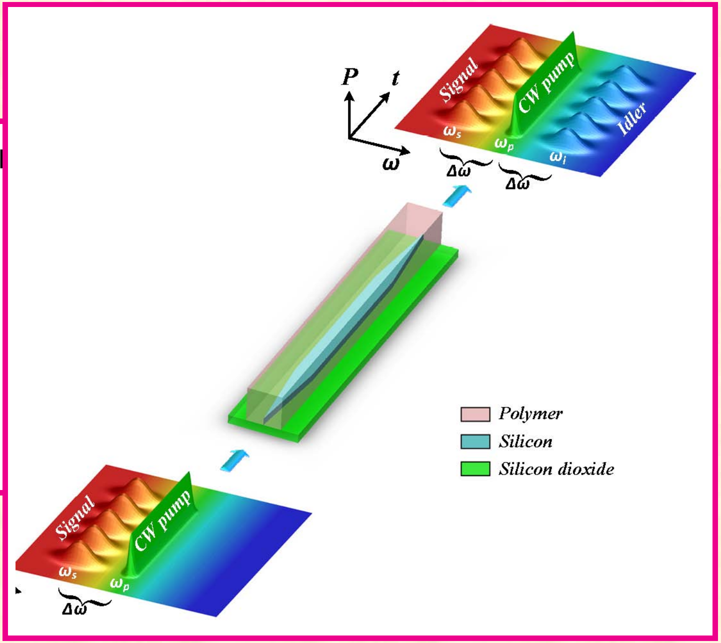


Rong et al., Nature Photonics **1**, 232 (2007)

Four-Wave Mixing (FWM)

Pump and signal launched into a silicon waveguide





Hu et al., Opt. Exp. **21**, 19886 (2011).

Energy conservation

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

Momentum conservation

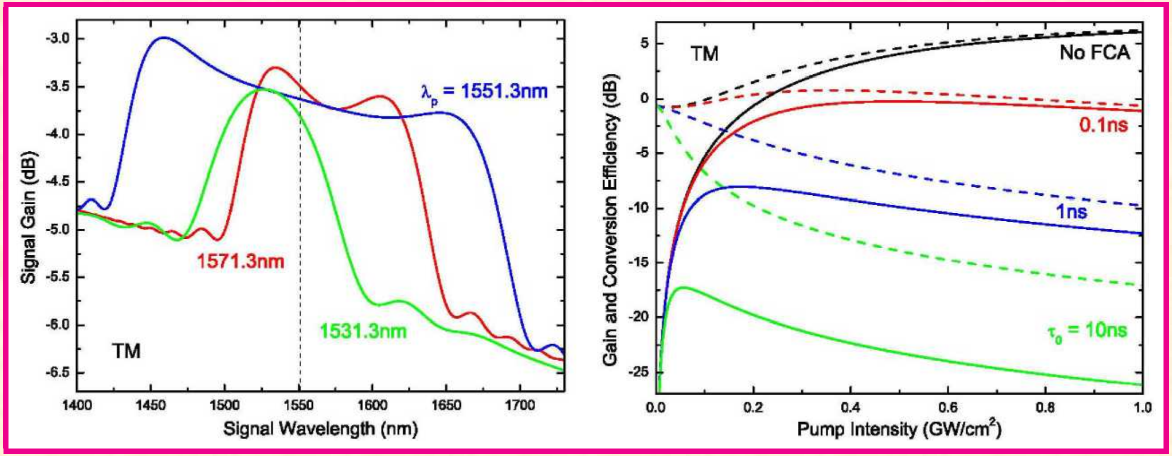
$$\beta_1 + \beta_2 = \beta_3 + \beta_4$$

Parametric Amplifiers

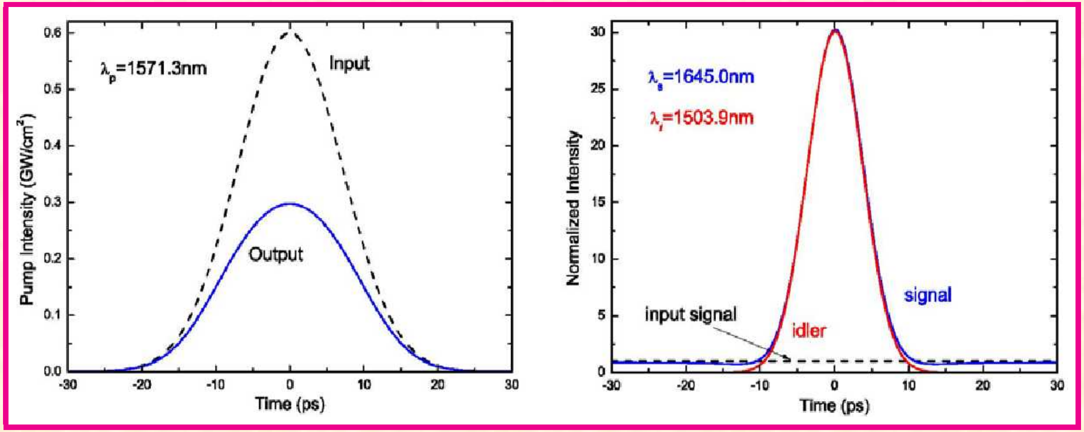
- FWM can be used to amplify a weak signal.
- Pump power is transferred to signal through FWM.
- The idler (generated as a byproduct) acts as a copy of the signal at a new wavelength (useful for wavelength conversion).
- Parametric amplifiers can provide gain at any wavelength using suitable pumps.
- They are also useful for all-optical signal processing.
- Optical fibers are often used, but the use of SOI waveguides would result in a much more compact device.
- Two-photon and free-carrier absorptions play an important role.

FWM Theory for Silicon Waveguides

- Full vector theory developed by Agrawal et al. in 2006: Opt. Exp. **14**, 4786 (2006).
- Relatively long carrier lifetime in silicon waveguides limits the FWM efficiency in the case of a CW pump.
- $\beta_2 < 0$ (red); $\beta_2 = 0$ (blue); $\beta_2 > 0$ (green).



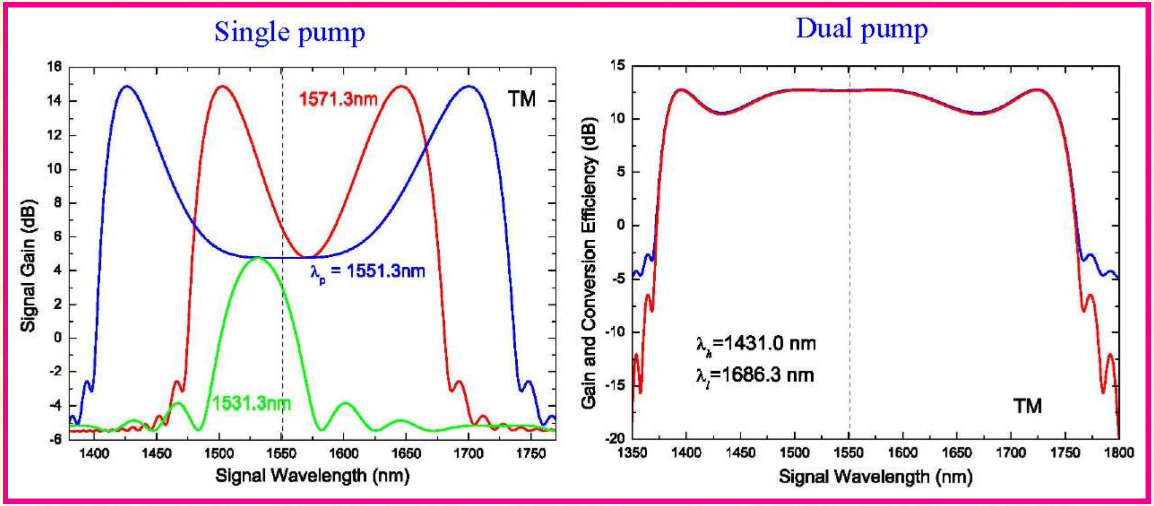
FWM with Short Pump Pulses



Lin et al., Opt. Exp. **14**, 4786 (2006)

- FCA is reduced significantly for pump pulses much shorter than carrier lifetime τ_c.
- Figure shows the case of 10-ps pump pulses with $\tau_c = 1$ ns.
- Phase-matching condition is satisfied even for signal that is shifted by 70 nm from the pump wavelength.

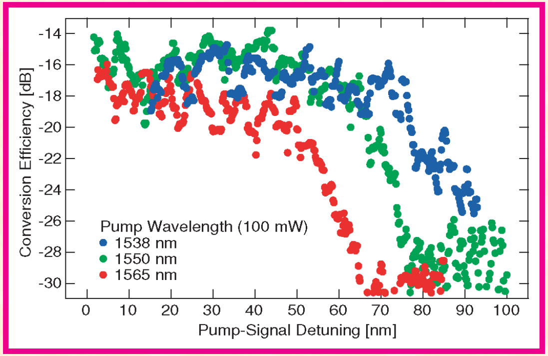
Single and Dual-Pump Configurations

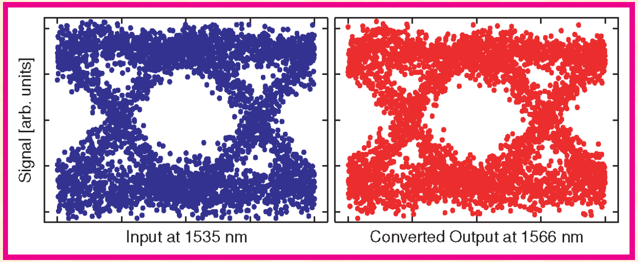


Lin et al., Opt. Express **14**, 4786 (2006)

- Parametric amplifiers with a large bandwidth can be realized by pumping an SOI waveguide with two pumps.
- This is possible because of a relatively short device length.
- Recent experiments with SOI waveguides are encouraging.

Wavelength Conversion of Telecom Channels

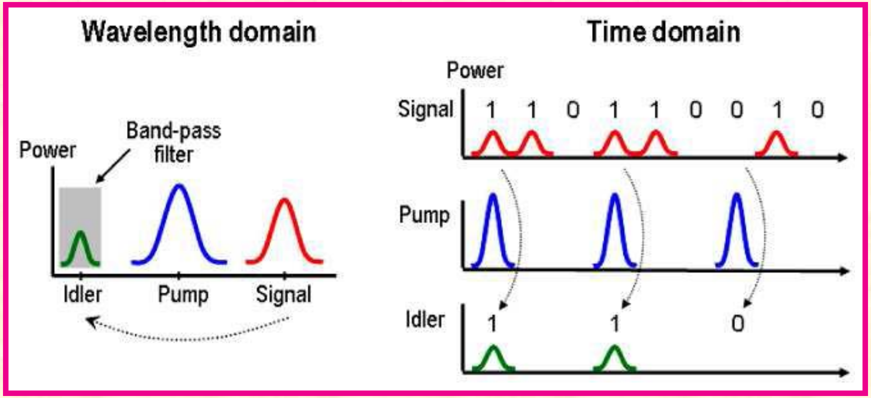


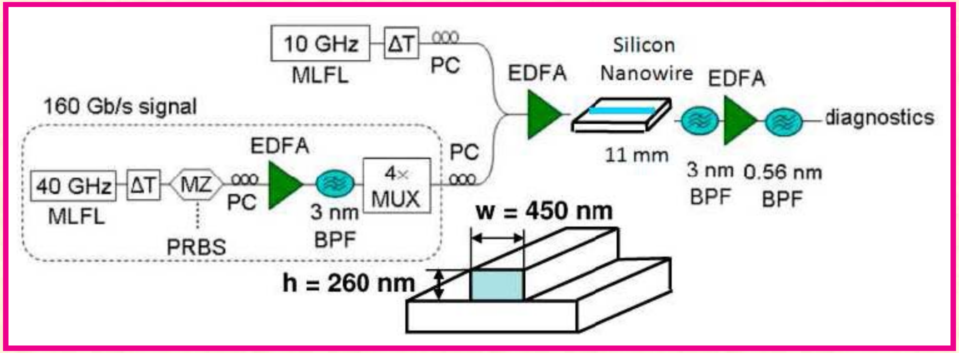


Foster et al., Opt. Express **15**, 12949 (2007)

- Dispersion control essential (300 nm$\times$750 nm device).
- FWM efficiency -15 dBm (CW pump);
  Conversion bandwidth $>$150 nm.
- Eye diagrams show no degradation when the wavelength of a 10-Gbs/s signal is converted using a 300 nm$\times$500 nm device.

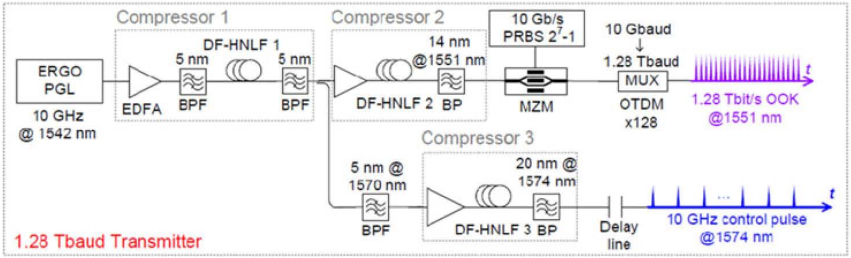
Demultiplexing at 160 Gb/s

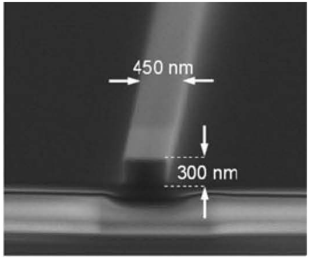


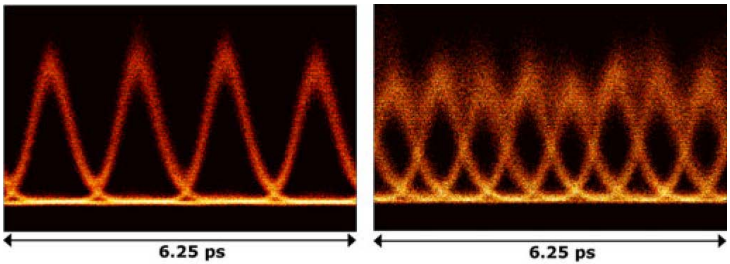


Li et al., Opt. Express **18**, 3905 (2010)

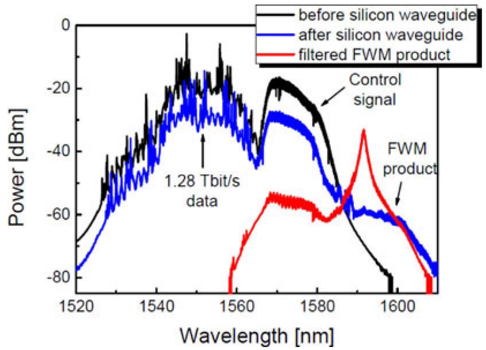
Demultiplexing at 1280 Gb/s







(a) (b)



Oxenlowe et al., IEEE JSTQE **18**, 996 (2012)

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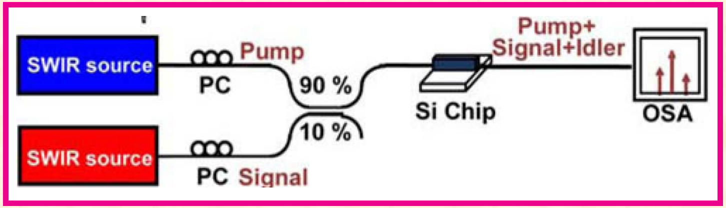
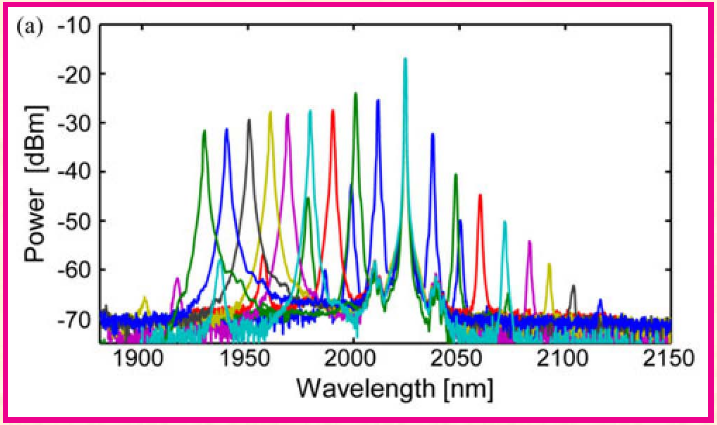
FWM in Mid-Infrared Region

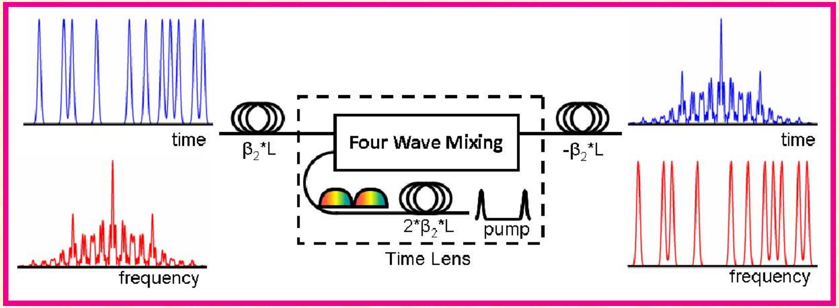


Zlatanovic et al., IEEE JSTQE **18**, 612 (2012)

- Pump and signal laser wavelengths near 2 μm.
- FWM efficiency of -5 dBm at 200 mW of pump power.
- Silicon waveguides used were up to 2.5 cm long.



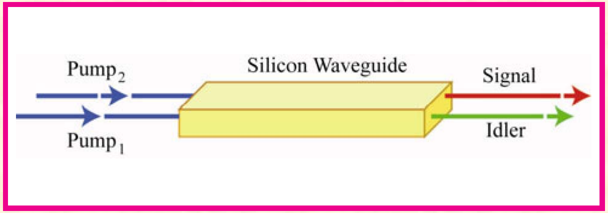
Time lens and Time Microscope



Petrillo et al., Opt. Exp. **21**, 508 (2013)

- FWM can be used to create a time lens (temporal analog of a lens)
- Chirp imposed on a pump pulse is transferred to the idler pulse.
- Time lens can be used to make a Fourier lens shown in Figure.
- It can also be used to build a time-domain microscope.
- Both temporal magnification and compression become possible with such time-domain imaging of optical pulses.

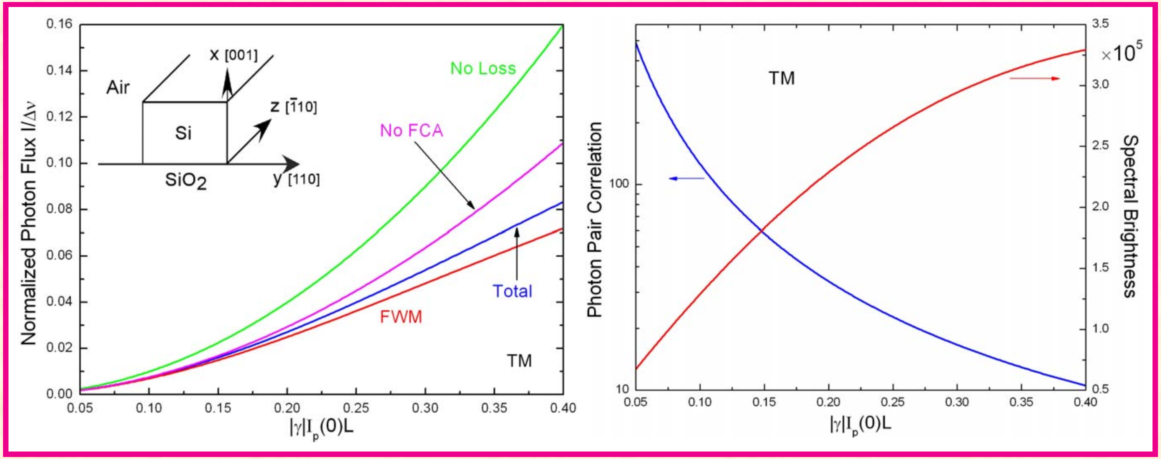
Photon-Pair Generation



Khasminskaya et al., Opt. Quant. Electron. **45**, 357 (2013)

- Spontaneous FWM in silicon waveguides can create entangled photon pairs.
- When pumped with one or two pump beams, the signal and idler photons are created **simultaneously** from quantum noise.
- Such entanglement is useful for a variety of quantum applications including quantum computing and quantum cryptography.
- Lin and Agrawal showed in 2006 that silicon waveguides work better than optical fibers: Lin et al., Opt. Lett. **31**, 3140 (2006).

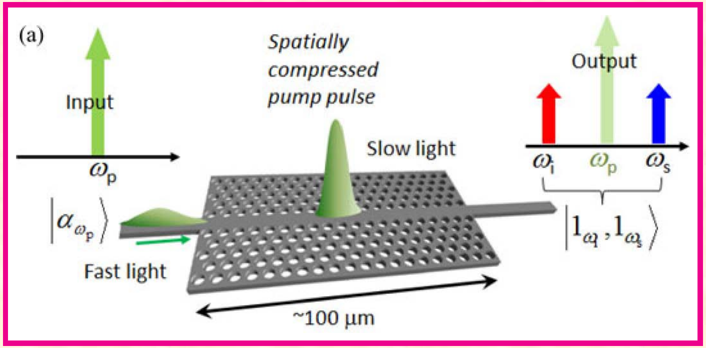
Photon-Pair Generation

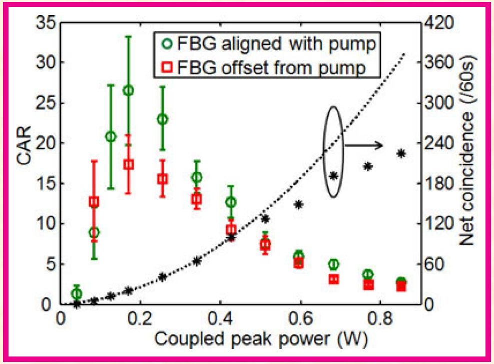


Lin et al., Opt. Lett. **31**, 3140 (2006)

- Spontaneous FWM in fibers creates entangled photon pairs but suffers from the noise induced by Raman scattering.
- The use of SOI waveguides avoids this problem because Raman scattering does not occur when TM mode is excited.
- Several experiments have confirmed our theoretical predictions.

Experimental Results





Xiong et al. JSTQE. **17**, 1676, (2012)

- Sharping et al. (Opt. Exp. **14**, 12388, 2006) used 5-ps pump pulses to generate good-quality photon pairs.
- Takesue et al. (Opt. Exp. **16**, 5721, 2008) used 90-ps pump pulses to create polarization-entangled photon pairs.
- A PhC waveguide with 10-ps pump pulses used in 2012 to generate photon pairs with high coincidence-to-accidental ratio (CAR).

Concluding Remarks

- Nonlinear effects in silicon waveguides can be used to make many active and passive components.
- SPM is useful for supercontinuum generation among other things.
- Cross-phase modulation can be used for optical switching, wavelength conversion, and optical signal processing.
- Nonlinear polarization rotation useful for making ultrafast photonic switches.
- Stimulated Raman scattering converts silicon waveguides into Raman amplifiers and lasers.
- Four-wave mixing is useful for wavelength conversion, tunable parametric delays, phase conjugation, and photon-pair generation.

Further Reading

- G. T. Reed, *Silicon Photonics: The State of the Art* (Wiley, 2008).
- L. Pavesi and D. J. Lockwood, *Silicon Photonics* (Springer, 2010).
- S. Fathpour and B. Jalali, *Silicon Photonics for Telecommunications and Biomedicine* (CRC, 2011)
- Q. Lin, O. J. Painter, G. P. Agrawal, "Nonlinear optical phenomena in silicon waveguides," Opt. Express **15**, 16604 (2007).
- R. M. Osgood et al., Adv. Opt. Photonics **1**, 162 (2009).
- IEEE J. Sel. Topics Quantum Electron., *Special issues on Silicon Photonics* (2006, 2008, 2010).
- IEEE J. Sel. Topics Quantum Electron., *Special issue on Photonics Packaging and Integration* (June 2011).

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